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Model Test on Impact of Surrounding Rock Deterioration on Segmental Lining Structure for Underwater Shield Tunnel with Large Cross-Section

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Abstract

Based on Guangzhou Shiziyang Tunnel, a large-scale model test of segment lining structure was conducted to study the impact of surrounding rock deterioration. The results showed the outflow or deterioration of surrounding rock at the hence could make the stress state at the bottom and crown more serious. And it is very important to provide effective surrounding rock resistance to ensure the safety of tunnel structure.

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*Keywoeds :*Underwater shield tunnel, surrounding rock deterioration, segmental lining structure, large cross-section.

1.Introduction

During shield tunnel construction, the stress of surrounding rock readjusts constantly caused by TBM excavation and driving. The stress redistribution may cause deterioration or failures occurred at certain region. The mechanical parameters and yield strength of surrounding rock may decrease in the region. Consequently, it may cause surrounding rock instable, even structure damage.

In actual projects, the surrounding rock instability and even segmental lining structure failure caused by TBM tunneling occurred frequently. For instance, an accident occurred at a work site of Shanghai Metro No.4 Line in 2003. As Ref. [1] and [2] described, the accident occurred after the main tunnel structure construction completed. When the connected aisle was constructing, about 270 m tunnel

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collapsed. Fig.1 shows the soil at left and right sides flowed into tunnel. And Fig.2 shows the failure state of segmental lining structure.

Fig.1 Scene of soil loss at both sides of shield tunnel

Fig.2 Failure state of segmental lining structure

It can clearly be seen, the outflow or deterioration of surrounding rock is harmful to the safety of shield tunnel. And to clarify the mechanical behavior of segmental lining structure under the interior state is important to ensure the safety of entire project.

Based on Guangzhou Shiziyang Tunnel project, a large-scale model test was carried out to discuss the impact of surrounding rock deterioration on mechanical behavior of segmental lining structure for underwater shield tunnel.

2.Project Overview

Guangzhou Shiziyang Tunnel project is a 10.8 km-long high-speed railway tunnel with double-tube two-single-track and the design velocity is up to 350 km/h. It is the first high-speed railway underwater using TBM method, and is the longest high-speed railway underwater tunnel in China.

Fig.3 shows the longitudinal profile of tunnel. The distributed strata at river bed consist of silty clay, muddy silty clay (Q), strongly weathered sandstone (W3, W4), and weakly weathered sandstone (W2). The tunnel is mainly passing through the surrounding rock of muddy silty clay and weakly weathered sandstone, abundant and high underground water (the highest hydraulic height is about 67 m).

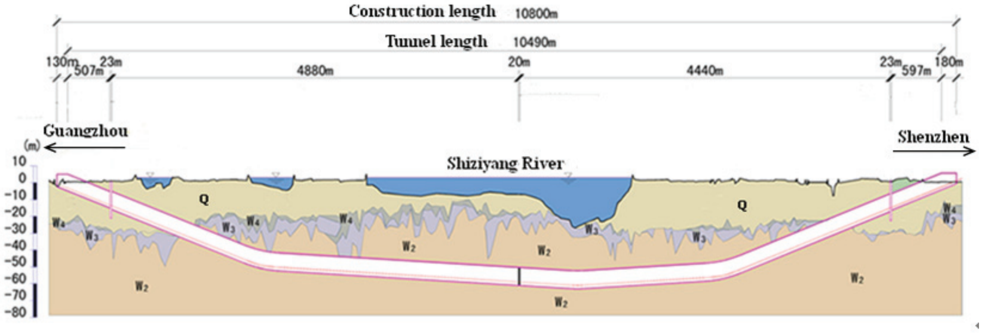


Fig.3 Longitudinal profile of Guangzhou Shiziyang Tunnel project

Fig.4 shows the segment layout of Guangzhou Shiziyang Tunnel. Segment external diameter is 10.8 m, internal diameter is 9.8 m, width is 2.0 m, and thickness is 0.5 m. One segment ring consists of 7 segments, including 5 standard segments (B1~B5), 2 adjacent segments (L1, L2), and 1 key segment (F). One ring consists of 24 M36 circumferential bolts and 22 M36 longitudinal bolts. The central angle of key segment is 16°21′49.09″. The adjacent segments and the standard segments have the same central angle as 49°5′27.27″.

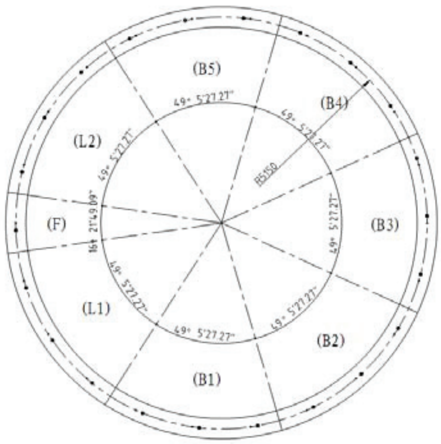


Fig.4 Segment layout of Guangzhou Shiziyang Tunnel

3.Model Test Design

3.1.Test Principles and Materials

Taking geometric similarity ratio C_l=20 and bulk density similarity ratio C_γ=1 as basic similarity ratio, full similarity controlling all physical and mechanical parameters in the scope of elasticity are realized (refer to Eq.1 and Eq.2).

$$C_\mu = C_\varepsilon = C_\varphi = 1 \tag{1}$$

$$C_R = C_\sigma = C_C = C_E = 20 \tag{2}$$

Where, μ, ε and φ are Poisson ratio, strain and friction angle respectively, R, σ, C and E are intensity, stress, cohesion force and elastic modulus respectively. Similar soil material is prepared by a mixture of barite powder, quartz sand, river sand, rosin and lubricating oil. Similar lining material is prepared by a mixture of water, gypsum and diatomite with the quality ratio of 1:1.40:0.1. The segment joint is simulated according to set an open slot with a certain depth at the position of longitudinal seam, so as to weakening the bending rigidity of the whole ring. The ring joint is simulated by steel bolts with 4mm in diameter and 30mm in length, considered that it is no dislocation between the rings (Fig.5).

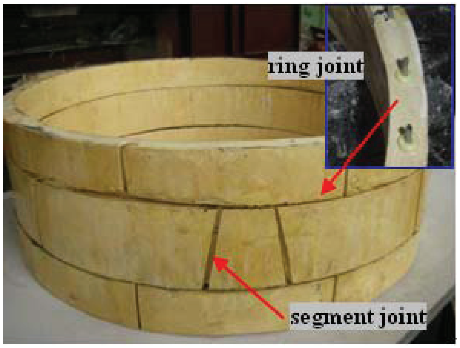


Fig.5 Model of segment lining structure

3.2. Test Devices

1) Shield Tunnel-Ground Simulation Facility [3,4]: The photo of the shield tunnel-ground simulation facility is shown in Fig.6. The overall test platform is 6 meters long, 6 meters wide and 2.55 meters high. The loading mode is a horizontal type. The structure and soil are under plane strain condition by the force of vertical jacks and counterforce frame. Different stress field applied on the segment lining is conducted by the force horizontal jacks separately. All of the jacks are controlled by hydraulic pressure. To reduce the friction between similar soil and e test platform, the face of steel plate is smeared with butter.

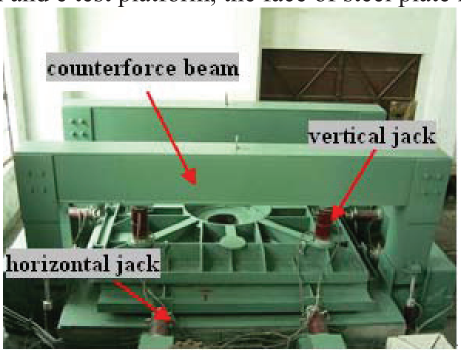


Fig.6 Tunnel-ground complex simulation facility

2) Water Pressure Simulation Device: Typically, external hydrostatic pressure a circular tunnel suffered is similar to elliptical, it can be decomposed into uniform parts and un-uniform parts [3], shown as Fig.7.

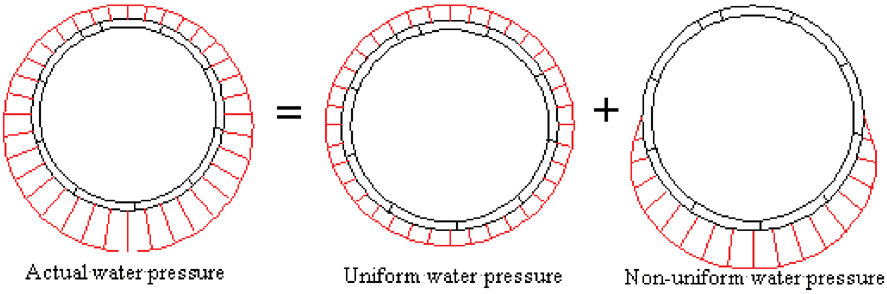
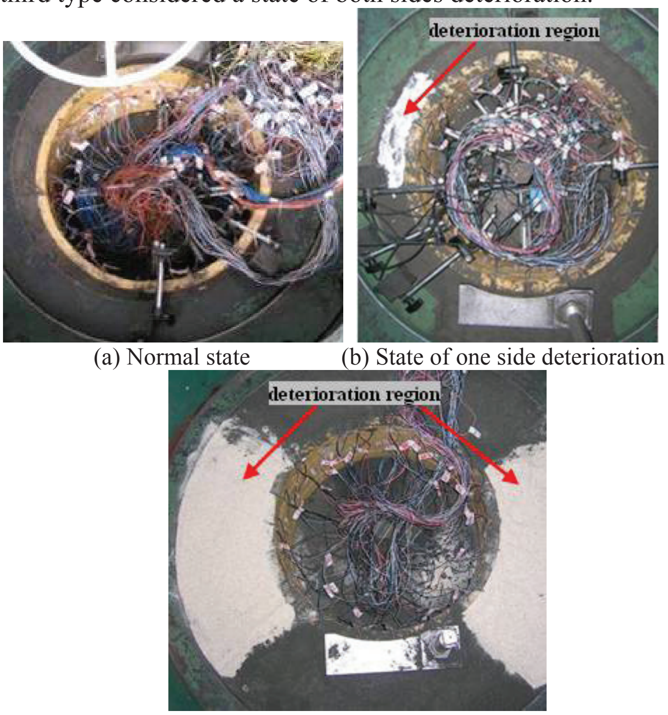


Fig.7 Plot of simulating water pressure

For underwater shield tunnel with large cross-section, the effect and mechanism of non-uniform water pressure on the lining can not be ignored [5]. In the model test, the uniform and non-uniform water pressures are conducted by hoop upon the whole ring and by stretching upon the arch bottom respectively.

3.3. Test Series

There were 3 types of surrounding rock simulated in the model test, shown in Fig.8. The first type was normal surrounding rock without deterioration; the second type considered a state of one side deterioration; and the third type considered a state of both sides deterioration.



(c) State of both sides deterioration

Fig.8 Plot of 3 types of surrounding rock

The soil in the deterioration region was mixture of quartz sand and river sand. It was loose and has the proporty of high compression and liquidity. So the case of loss of ground resistance could be silumilated efficiently.

4.Test Results and Analysis

During the different load case, the displacement and inner force of the same structure differed from each other. Tab.I shows the test results of maximum deformation, positibe and negative bending moments and axial force.

TABLE I Test Results of Different Load Case

(NS: Normal state; ODS: State of one side deterioration; BDS: State of both sides deterioration)

Property	NS	ODS	BDS
Maximum deformation (mm)	12.93	30.16	33.62
Maximum positive moment (kN·m)	843	1330	1810
Maximum negative moment (kN·m)	-570	-1260	-1790
Maximum axial force (kN)	5670	5410	5350
Minimum axial force (kN)	4550	4260	4120

Compared the maximum value of test results, the deformation and bending moment are significantly different. Considering the deformation, the maximum value of one side deterioration state was 133% larger than that of normal state, the maximum value of both sides deterioration state was 133% larger than that of normal state was 199% larger than that of normal state.

Considering the bending moment, the maximum value of one side deterioration state was 57.8% larger than that of normal state, the maximum value of both sides deterioration state was 115% larger than that of normal state was 199% larger than that of normal state. Considering the axial force, there were less differences than that of deformation and bending moment.

So the effect of surrounding rock on deformation and bending moment was more sensitive than that of axial force. Along with the surrounding rock deterioration, the safety of tunnel structure rapidly reduced.

Fig.9, Fig.10 and Fig.11 show the distribution and change of deformation, bending moment and axial force under different load cases.

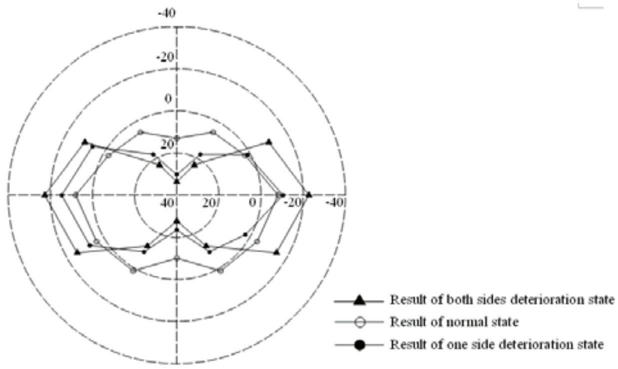


Fig.9 Test results of displacement under different load cases (Unit: mm)

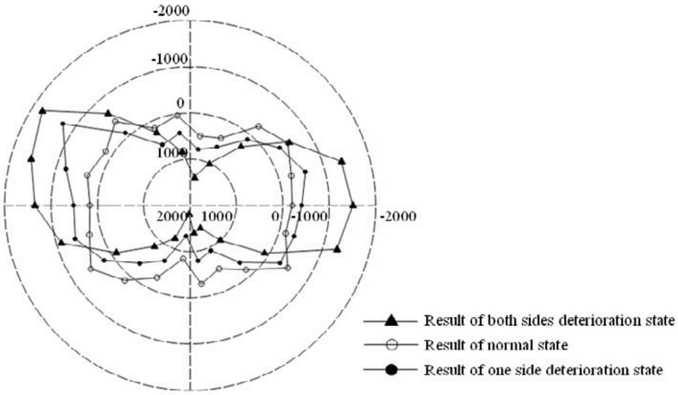


Fig.10 Test results of bending moment under different load cases (Unit: kN • m)

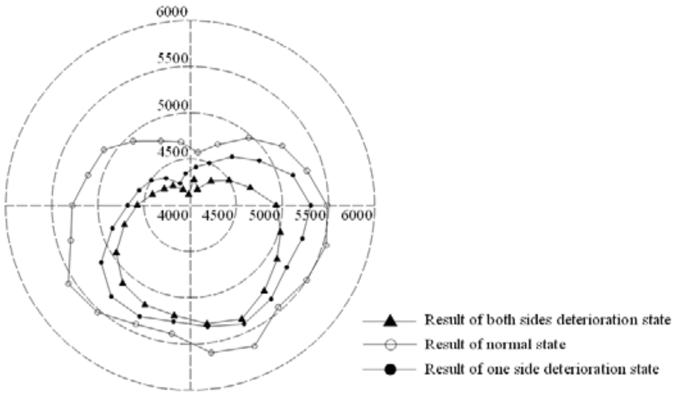


Fig.11 Test results of axial force under different load cases (Unit: kN)

It can clearly be seen, when the surrounding rock deteriorated, the deformation and bending moment grew larger at the deterioration region. The axial force decreased slightly in the region. In a word, it is very important to provide effective surrounding rock resistance for the safety of tunnel structure.

When the shield tunnel structure damaged under the state of both sides deterioration, the failure state of segmental lining structure was described in Fig.12. The crack firstly occurred at the bottom and crown, in B1 and B5. With the increase of load, the crushing zone appeared at the hence. After that, then new cracks occurred at B2 and B3, and then the tunnel damaged. Owing to the large displacement, crack occurred rarely at the hence. The outflow or deterioration of surrounding rock could release load to some extent, but the loss of soil resistance might make the stress state at the bottom and crown more serious.

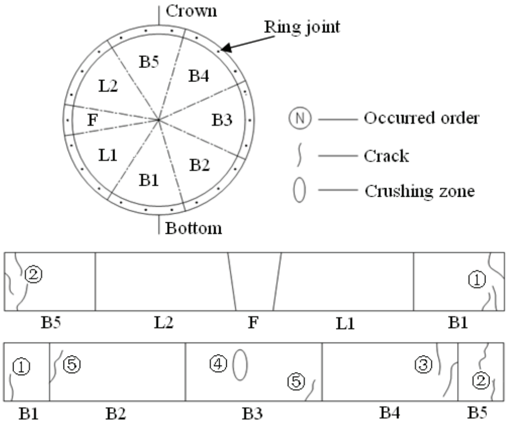


Fig.12 Sketch of failure characteristic of lining

5.Conclusions

Based on Guangzhou Shiziyang Tunnel, a large-scale model test of segment lining structure is conducted to study the impact of surrounding rock deterioration. And some suggestions about are proposed below.

(1) The deformation and inner force is sensitive to the deterioration of surrounding rock, it is very important to provide effective surrounding rock resistance to ensure the safety of tunnel structure.

(2) The outflow or deterioration of surrounding rock at the hence could release load to some extent, but the loss of soil resistance might make the stress state at the bottom and crown more serious.

6.Acknowledgment

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